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(54) **IGNITION DEVICE**

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See application file for complete search history.

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(57) **ABSTRACT**

An ignition device according to the present invention includes: an ignition plug, which includes a first electrode, a second electrode, and a dielectric body arranged between the electrodes; an AC power supply configured to generate an AC voltage to be applied between the electrodes; a thermal plasma detection portion configured to output a thermal plasma occurrence signal when thermal plasma has occurred between the electrodes; and an application time period determination portion configured to determine an application time period for the AC voltage during one cycle of the internal combustion engine in advance before the application, and when the thermal plasma occurrence signal is received while the AC voltage is being applied based on

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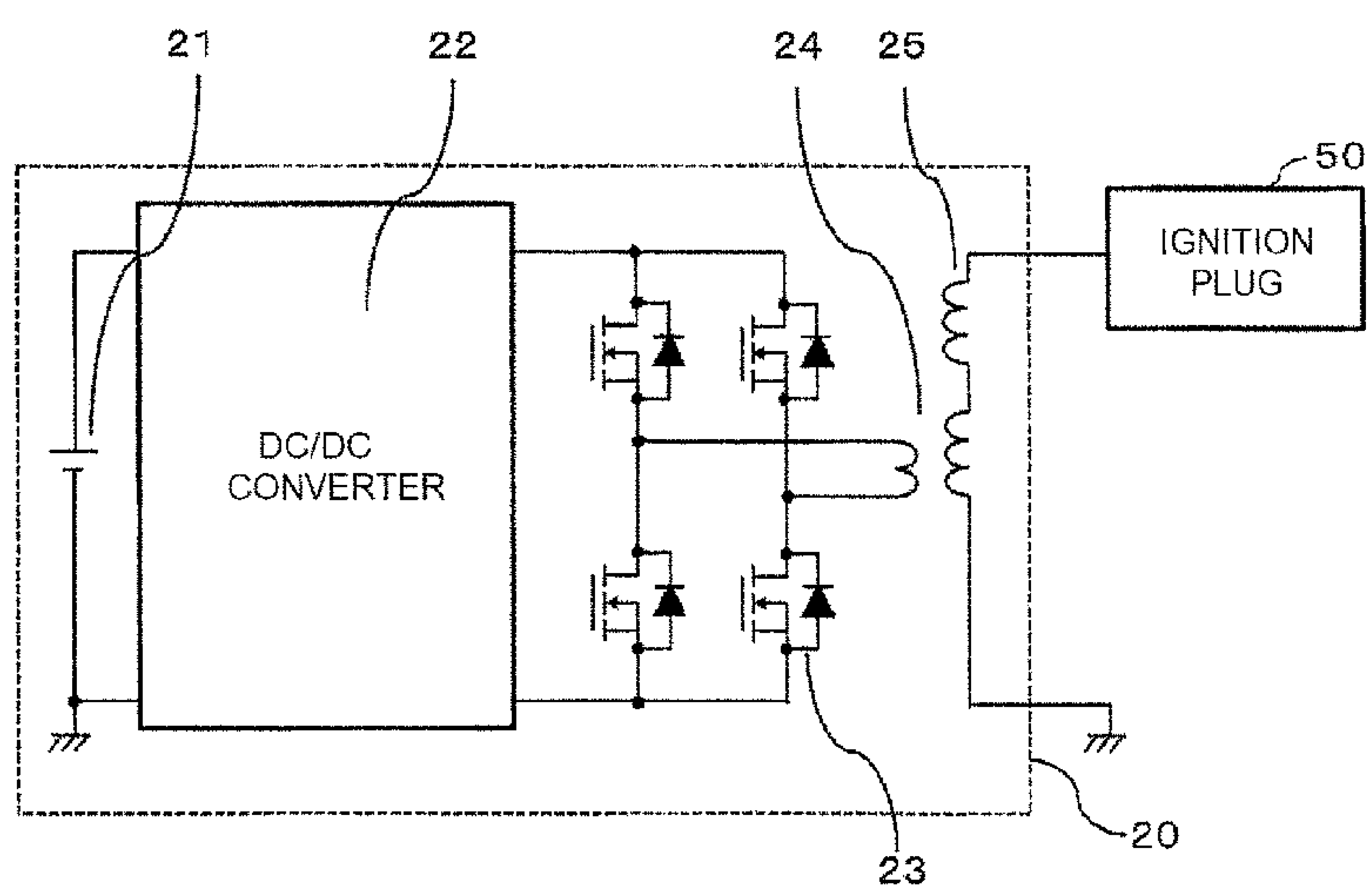

the application time period, change the application time period so as to shorten the application time period.

8 Claims, 6 Drawing Sheets

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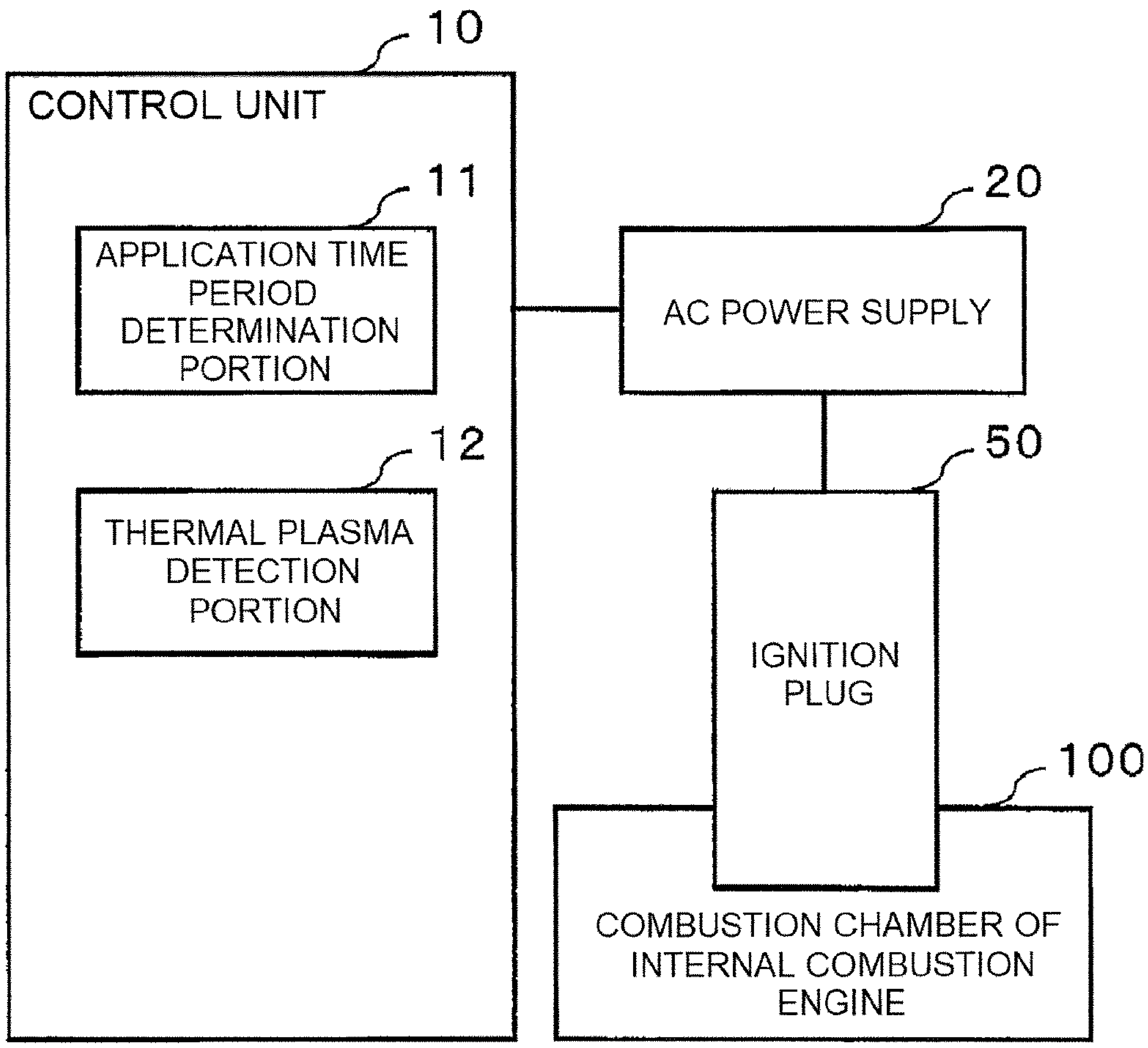
10
CONTROL UNIT
11
APPLICATION TIME PERIOD DETERMINATION PORTION
12
THERMAL PLASMA DETECTION PORTION
20
AC POWER SUPPLY
50
IGNITION PLUG
100
COMBUSTION CHAMBER OF INTERNAL COMBUSTION ENGINE

FIG. 1

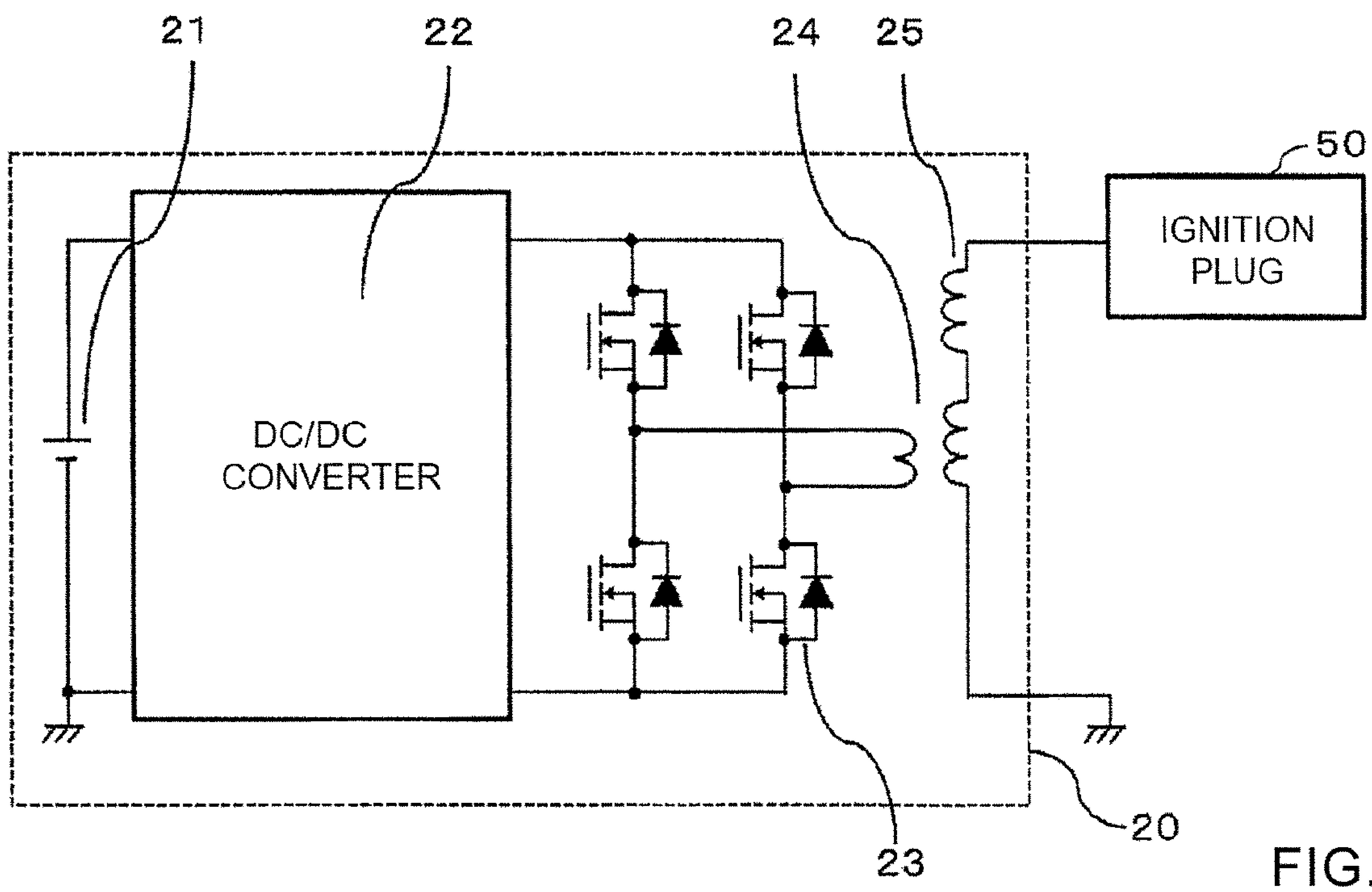
21
22
24
25
50
IGNITION PLUG
DC/DC CONVERTER
20
23

FIG. 2

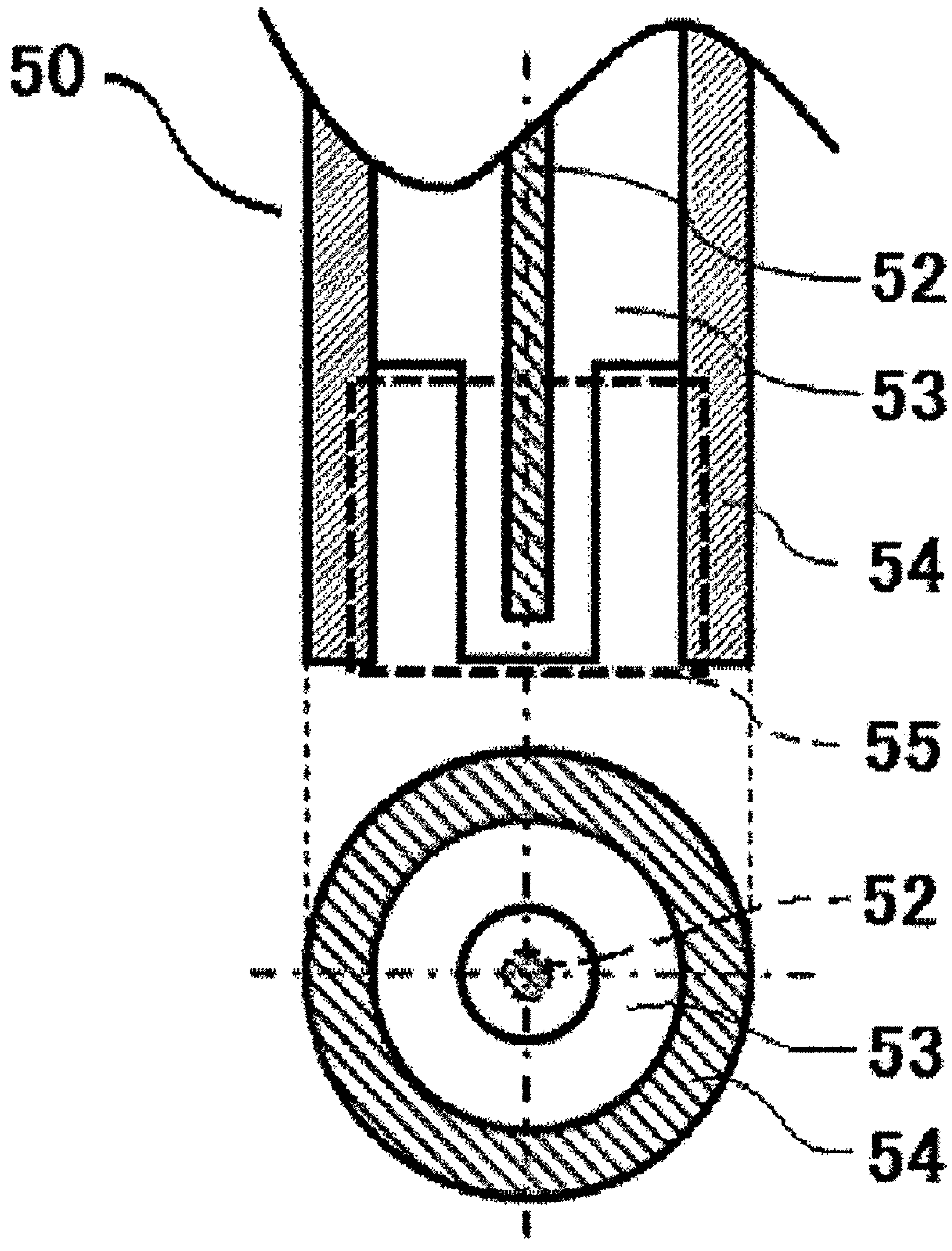
50
52
53
54
55
52
53
54

FIG. 3

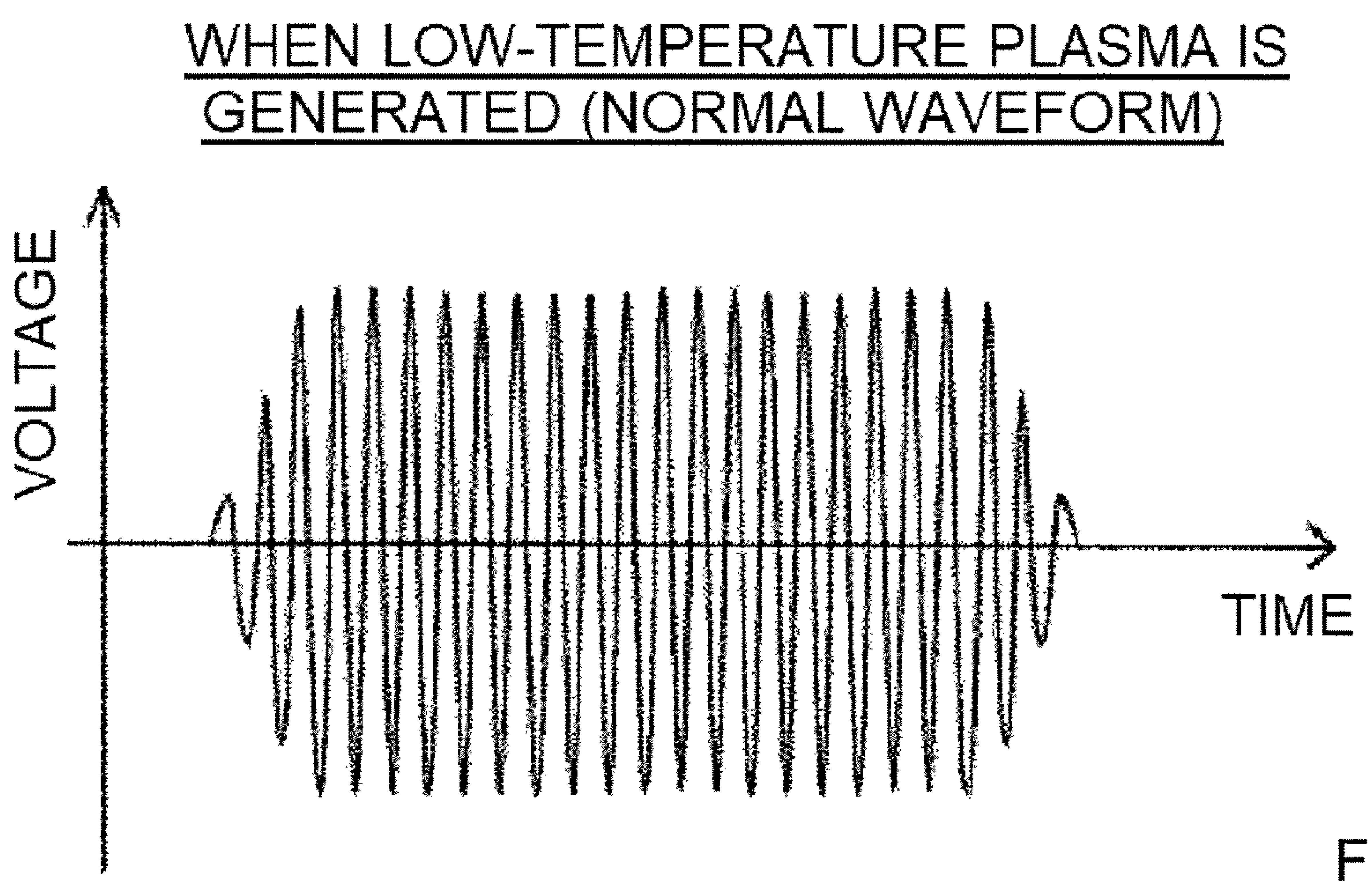
WHEN LOW-TEMPERATURE PLASMA IS GENERATED (NORMAL WAVEFORM)
VOLTAGE
TIME

FIG 4

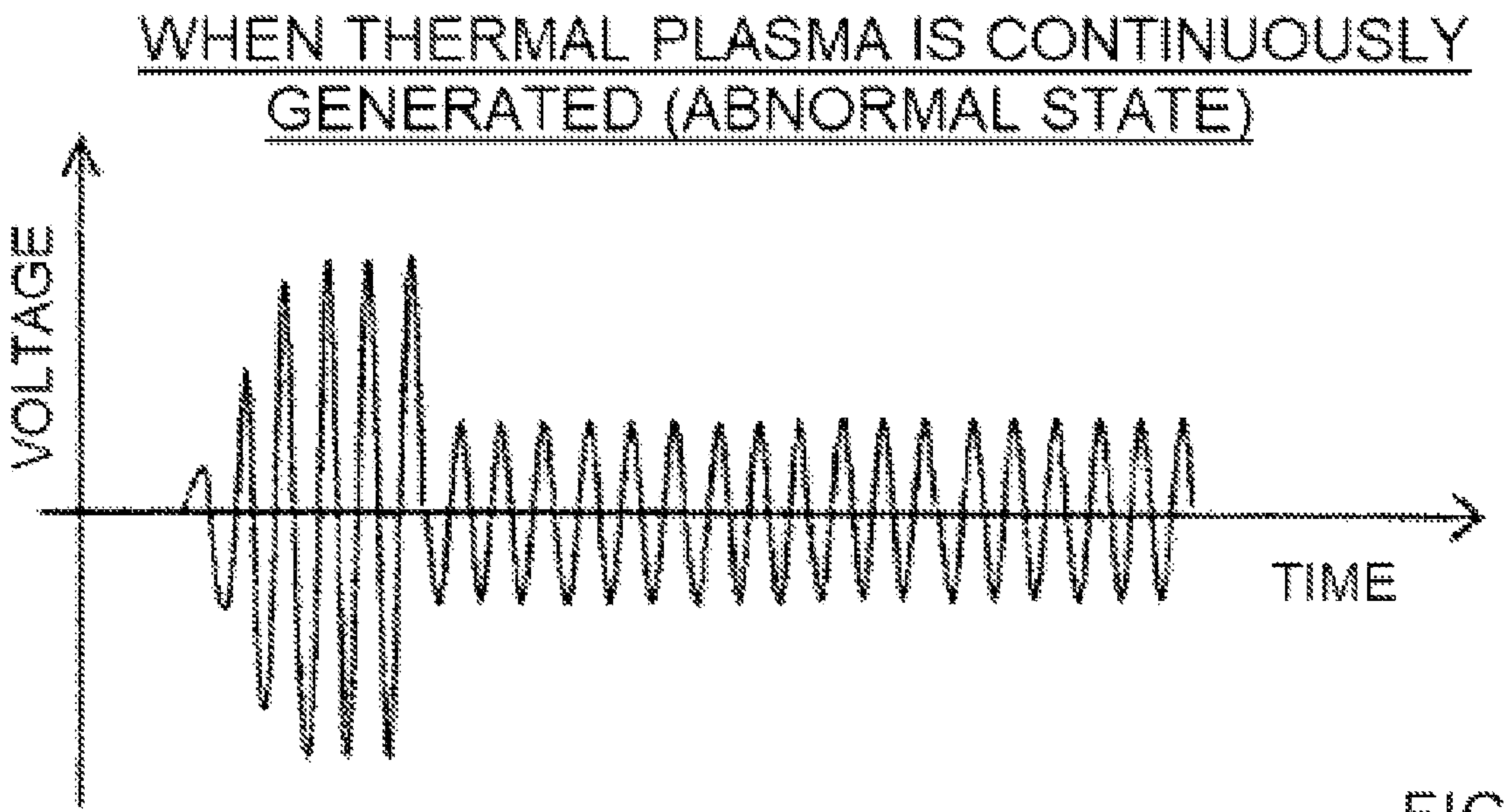
WHEN THERMAL PLASMA IS CONTINUOUSLY GENERATED (ABNORMAL STATE)
VOLTAGE
TIME

FIG. 5

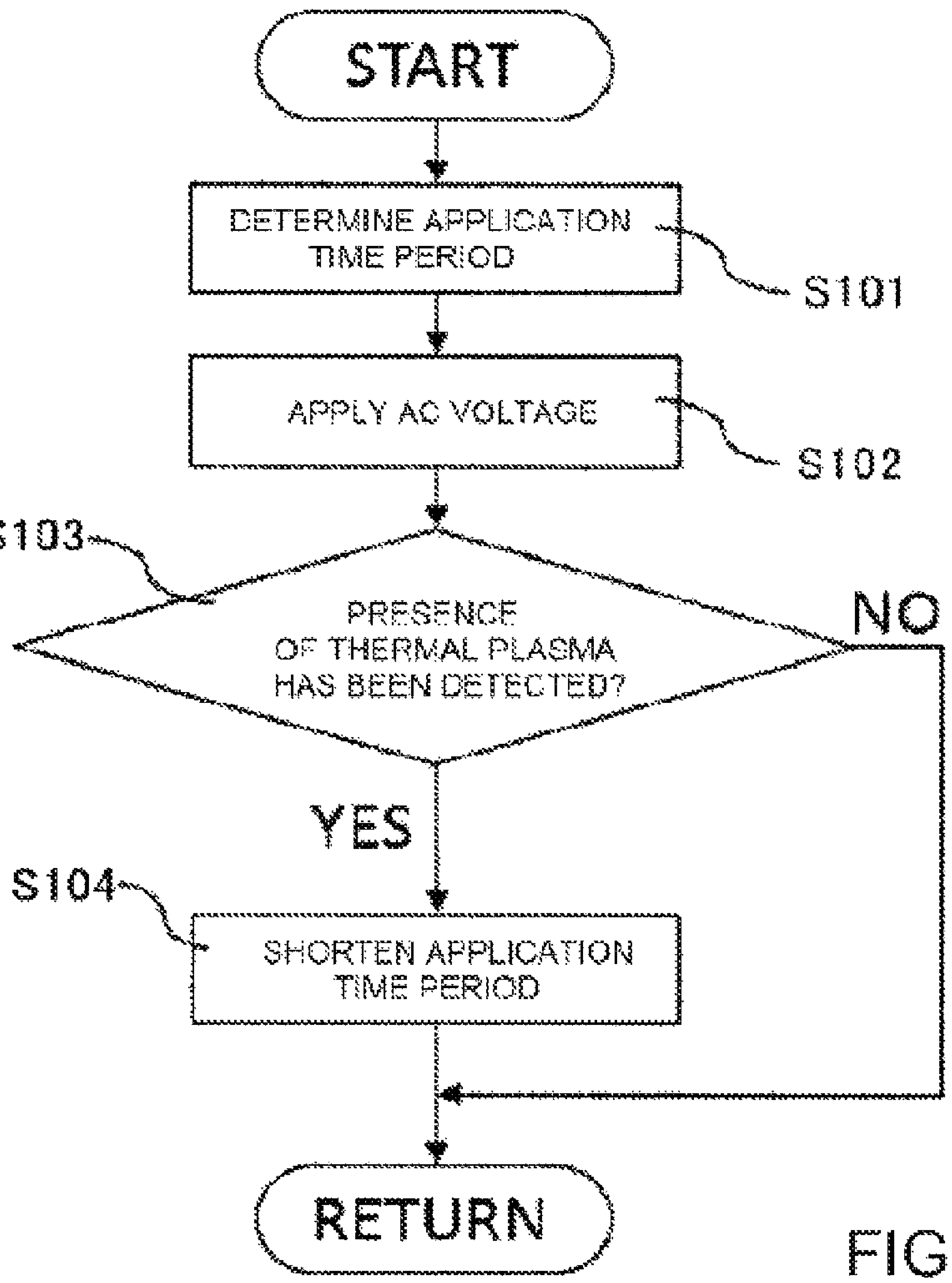
START
DETERMINE APPLICATION TIME PERIOD
S101
APPLY AC VOLTAGE
S102
S103
PRESENCE OF THERMAL PLASMA HAS BEEN DETECTED?
NO
YES
S104
SHORTEN APPLICATION TIME PERIOD
RETURN

FIG.6

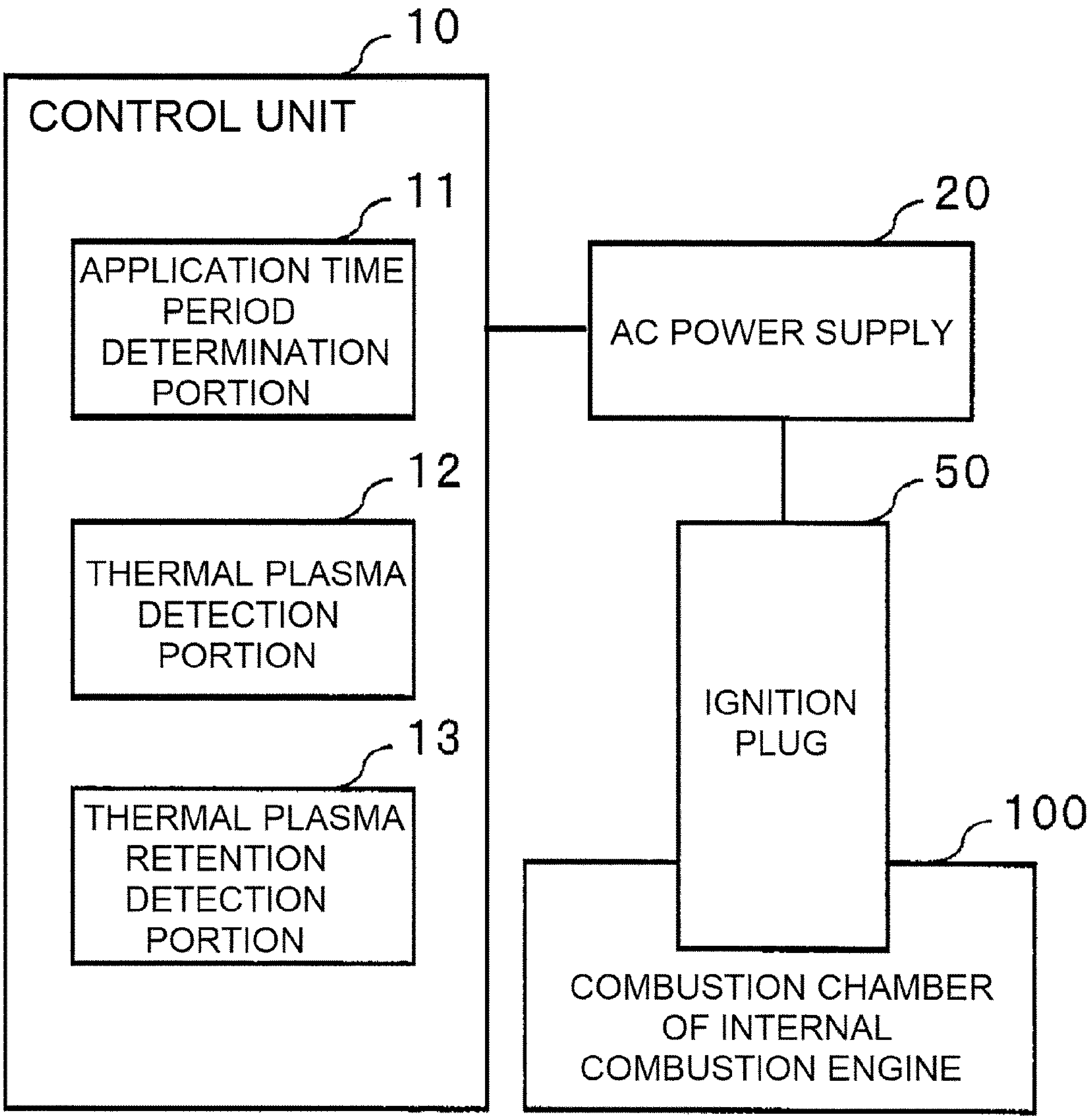
10
CONTROL UNIT
11
APPLICATION TIME PERIOD DETERMINATION PORTION
12
THERMAL PLASMA DETECTION PORTION
13
THERMAL PLASMA RETENTION DETECTION PORTION
20
AC POWER SUPPLY
50
IGNITION PLUG
100
COMBUSTION CHAMBER OF INTERNAL COMBUSTION ENGINE

FIG. 7

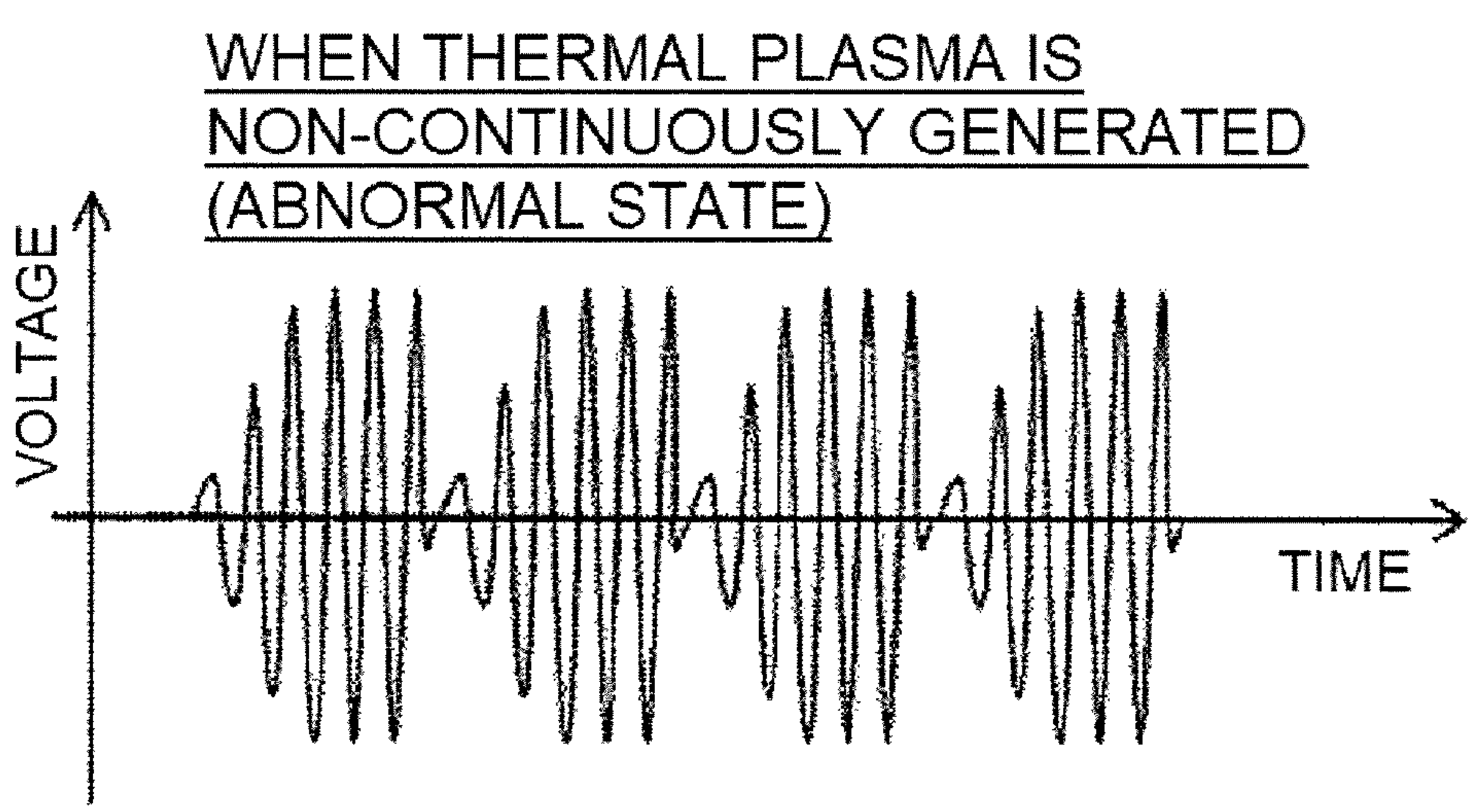
WHEN THERMAL PLASMA IS NON-CONTINUOUSLY GENERATED (ABNORMAL STATE)
VOLTAGE
TIME

FIG. 8

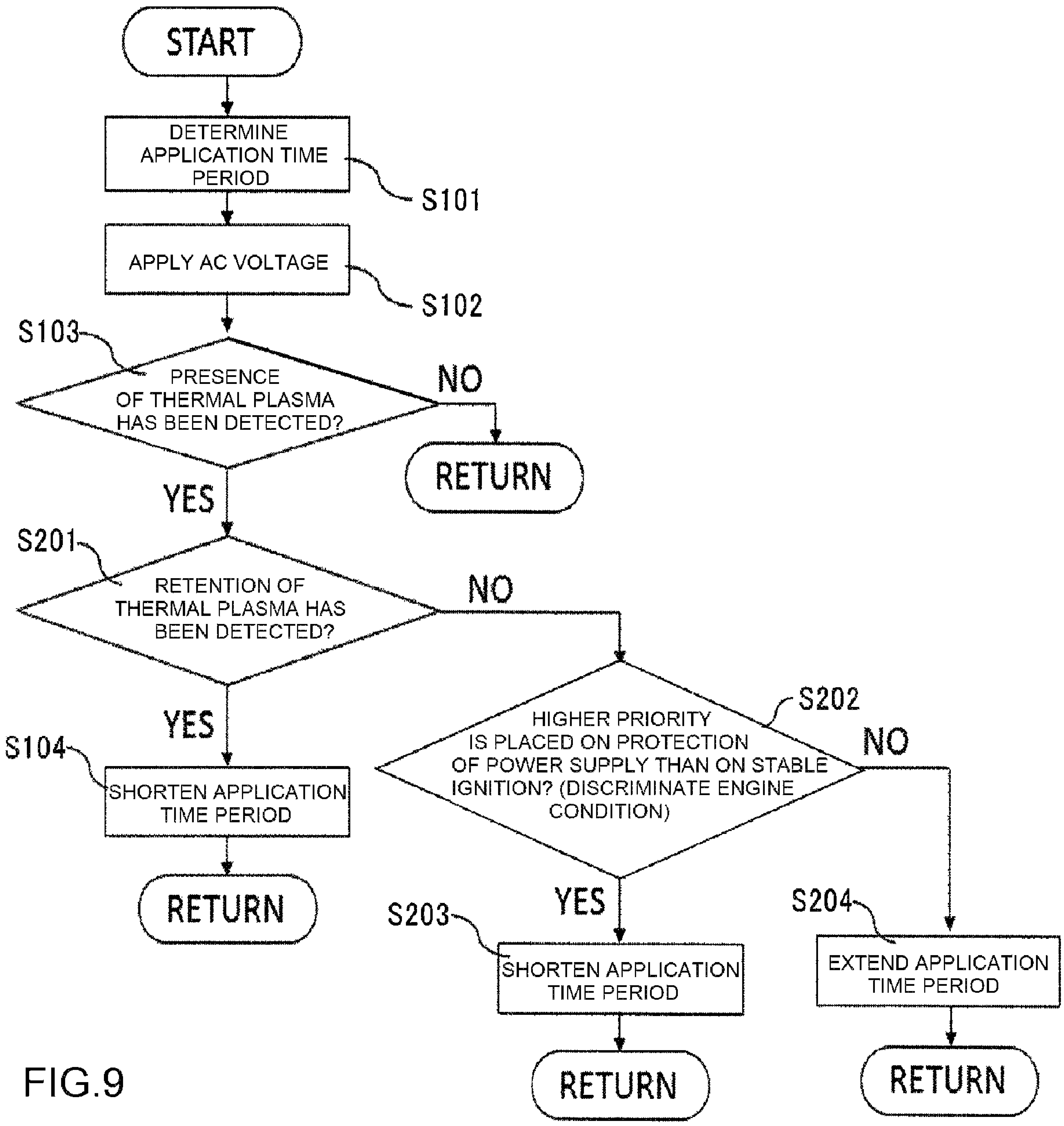
START
DETERMINE APPLICATION TIME PERIOD
S101
APPLY AC VOLTAGE
S102
S103
PRESENCE OF THERMAL PLASMA HAS BEEN DETECTED?
NO
RETURN
YES
S201
RETENTION OF THERMAL PLASMA HAS BEEN DETECTED?
NO
S202
HIGHER PRIORITY IS PLACED ON PROTECTION OF POWER SUPPLY THAN ON STABLE IGNITION? (DISCRIMINATE ENGINE CONDITION)
NO
YES
S104
SHORTEN APPLICATION TIME PERIOD
RETURN
YES
S203
SHORTEN APPLICATION TIME PERIOD
RETURN
S204
EXTEND APPLICATION TIME PERIOD
RETURN

FIG.9

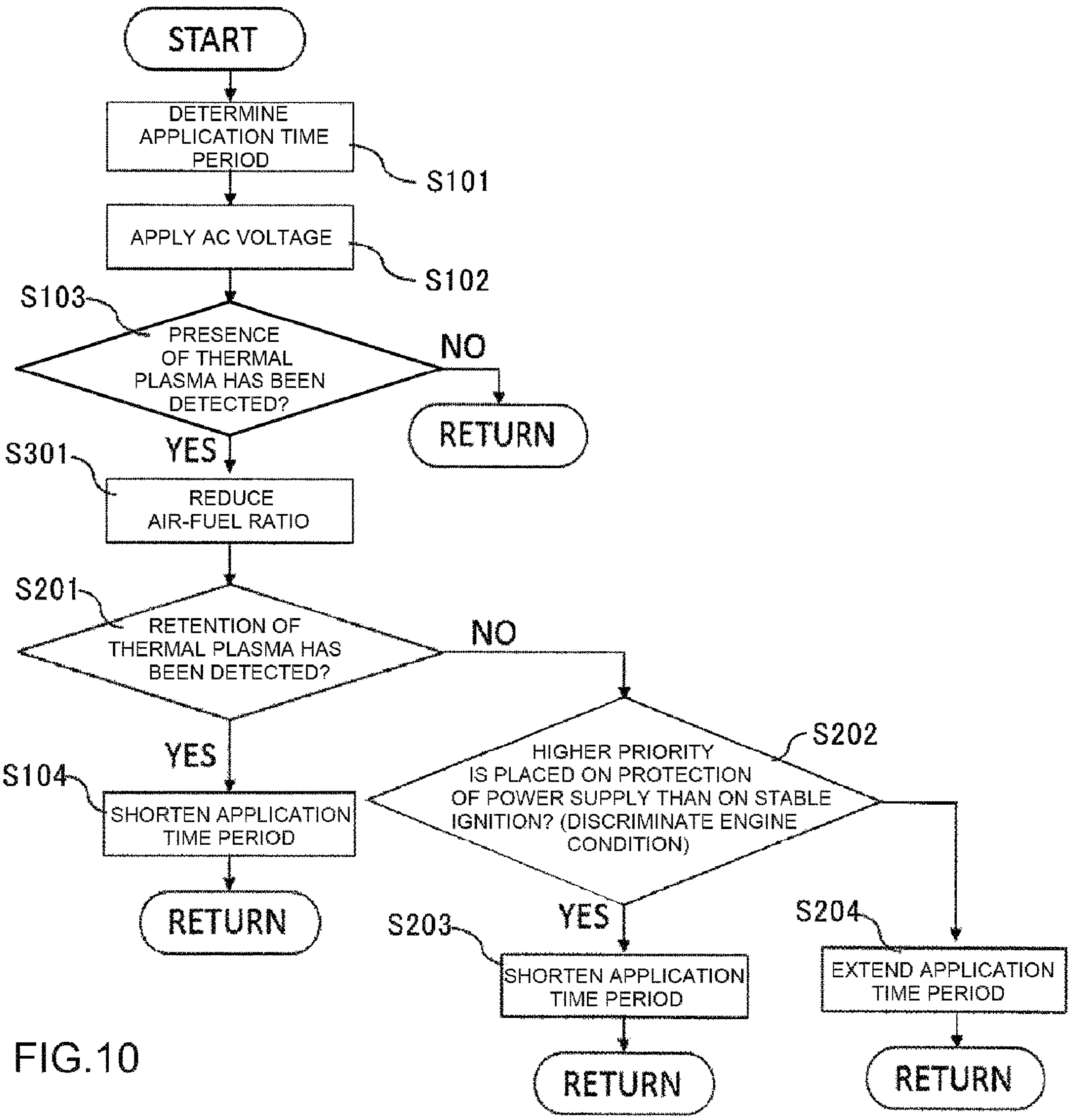
START
DETERMINE APPLICATION TIME PERIOD
S101
APPLY AC VOLTAGE
S102
S103
PRESENCE OF THERMAL PLASMA HAS BEEN DETECTED?
NO
RETURN
YES
S301
REDUCE AIR-FUEL RATIO
S201
RETENTION OF THERMAL PLASMA HAS BEEN DETECTED?
NO
YES
S104
SHORTEN APPLICATION TIME PERIOD
RETURN
S202
HIGHER PRIORITY IS PLACED ON PROTECTION OF POWER SUPPLY THAN ON STABLE IGNITION? (DISCRIMINATE ENGINE CONDITION)
YES
S203
SHORTEN APPLICATION TIME PERIOD
RETURN
S204
EXTEND APPLICATION TIME PERIOD
RETURN

FIG.10

IGNITION DEVICE

CROSS-REFERENCE TO RELATED APPLICATIONS

The present application is based on PCT filing PCT/JP2018/019978, filed May 24, 2018, which claims priority to JP 2017-216413, filed Nov. 9, 2017, the entire contents of each are incorporated herein by reference.

TECHNICAL FIELD

The present invention relates to an ignition device for an internal combustion engine, which uses a barrier discharge.

BACKGROUND ART

In an internal combustion engine, ignition is unstable under a lean combustion environment or a high exhaust gas recirculation (EGR) environment, which aims at an improvement in fuel efficiency. In view of this, there is proposed a barrier-discharge-type ignition device capable of volumetric ignition (see, for example, Patent Literature 1).

CITATION LIST

Patent Literature

[PTL 1] JP 2014-513760 A1

SUMMARY OF INVENTION

Technical Problem

As the invention according to Patent Literature 1, there is proposed a technology for detecting a transition from low-temperature plasma to thermal plasma to interrupt the thermal plasma in an ignition device configured to form low-temperature plasma through use of a short-pulse power supply and an ignition plug having all metal electrodes exposed to an air-fuel mixture.

However, the invention according to Patent Literature 1 relates to the ignition device configured to generate a barrier discharge through use of the AC power supply and the ignition plug having at least one of the electrodes covered with a dielectric body. Therefore, when the dielectric body electrically breaks down, there is no way to intentionally generate low-temperature plasma, thereby inhibiting the ignition device from performing its normal operation. In view of this, it is required to employ a control scheme for avoiding a failure of the ignition device while maintaining minimum ignition performance under an abnormal state in which the dielectric body has electrically broken down.

The present invention has been made in order to solve the above-mentioned problem, and has an object to obtain a barrier-discharge-type ignition device capable of avoiding a failure while maintaining minimum ignition performance even when a dielectric body of an ignition plug electrically breaks down.

Solution to Problem

An ignition device according to one embodiment of the present invention includes: an ignition plug, which is arranged in an internal combustion engine, and includes a first electrode, a second electrode, and a dielectric body arranged between the first electrode and the second electrode; an AC power supply configured to generate an AC voltage to be applied between the first electrode and the second electrode; a thermal plasma detection portion configured to detect whether thermal plasma has occurred between the first electrode and the second electrode, and when the thermal plasma is detected, output a thermal plasma occurrence signal; and an application time period determination portion configured to determine an application time period for the AC voltage during one cycle of the internal combustion engine in advance before the application, and when the thermal plasma occurrence signal is received while the AC voltage is being applied based on the application time period, change the application time period so as to shorten the application time period.

Advantageous Effects of Invention

According to the present invention, there is provided a configuration for performing control to shorten a predetermined application time period when an occurrence of thermal plasma is detected while the AC voltage is being applied to the ignition plug based on the application time period. As a result, it is possible to obtain a barrier-discharge-type ignition device capable of avoiding a failure while maintaining minimum ignition performance even when the dielectric body of the ignition plug electrically breaks down.

BRIEF DESCRIPTION OF DRAWINGS

FIG. **1** is a schematic diagram for illustrating an example of a configuration of an ignition device according to a first embodiment of the present invention.

FIG. **2** is a circuit diagram for illustrating an example of an AC power supply **20** in the first embodiment of the present invention.

FIG. **3** is a schematic view for illustrating an example of an ignition plug of the ignition device according to the first embodiment of the present invention.

FIG. **4** is a schematic diagram for illustrating an example of a waveform of an AC voltage to be applied to the ignition plug under a normal state in the ignition device according to the first embodiment of the present invention.

FIG. **5** is a schematic diagram for illustrating an example of a waveform of the AC voltage to be applied to the ignition plug under an abnormal state in the ignition device according to the first embodiment of the present invention.

FIG. **6** is a schematic flow chart for illustrating an example of a control flow of the ignition device according to the first embodiment of the present invention.

FIG. **7** is a schematic diagram for illustrating an example of a configuration of an ignition device according to a second embodiment of the present invention.

FIG. **8** is a schematic diagram for illustrating an example of a waveform of an AC voltage exhibited when thermal plasma intermittently occurs in the ignition device according to the second embodiment of the present invention.

FIG. **9** is a schematic flow chart for illustrating an example of a control flow of the ignition device according to the second embodiment of the present invention.

FIG. **10** is a schematic flow chart for illustrating an example of a control flow of an ignition device according to a third embodiment of the present invention.

DESCRIPTION OF EMBODIMENTS

An ignition device according to preferred embodiments of the present invention is described below with reference to the accompanying drawings.

First Embodiment

FIG. **1** is a schematic diagram for illustrating an example of a configuration of an ignition device according to a first embodiment of the present invention. The ignition device according to the first embodiment has a technical feature of being capable of igniting fuel with stability without causing a failure in the ignition device even when an ignition plug is damaged.

The ignition device illustrated in FIG. **1** includes a control unit **10**, an AC power supply **20**, and an ignition plug **50**. The AC power supply **20** and the ignition plug **50** are electrically connected to each other. One end of the ignition plug **50** is arranged in a combustion chamber **100** of an internal combustion engine. The AC power supply **20** generates an AC voltage. When an AC voltage is applied to the ignition plug **50**, the ignition plug **50** causes a barrier discharge to occur in the combustion chamber **100** of the internal combustion engine.

The control unit **10** is electrically connected to the AC power supply **20**. The control unit **10** also includes an application time period determination portion **11** configured to determine a time period during which an AC voltage is to be applied with one ignition, and a thermal plasma detection portion **12** configured to detect the presence or absence of thermal plasma at the ignition plug **50** to output the presence or absence as a thermal plasma occurrence signal.

The AC power supply **20** in the first embodiment has a function of converting a DC voltage into an AC voltage and a function of boosting the AC voltage. In this case, the AC voltage is not limited to a sine wave as long as a barrier discharge can be caused to occur, and may be a square wave.

FIG. **2** is a circuit diagram for illustrating an example of the AC power supply **20** in the first embodiment of the present invention. The AC power supply **20** illustrated in FIG. **2** includes a DC power supply **21**, a DC/DC converter **22**, switching elements **23**, a step-up transformer **24**, and a resonance coil **25**.

The DC power supply **21** used in the AC power supply **20** corresponds to a DC voltage of 12 V, which is a general automobile battery voltage. The AC power supply **20** boosts the DC voltage from the DC power supply **21** by 2 times to 40 times by the DC/DC converter **22**, then converts the DC voltage into an AC voltage through use of the switching elements **23**, and further boosts the AC voltage by the step-up transformer **24** and the resonance coil **25**. The conversion from DC into AC is performed by a full bridge circuit using a total of four switching elements **23**, two of which are connected in series, and the other two of which are connected in parallel.

In the first embodiment, the conversion from DC into AC is performed by a full bridge circuit, but a half bridge circuit may be used for the conversion. When the half bridge circuit is used, only two switching elements **23** are required, but a double voltage is applied to the switching elements **23** even with the same step-up ratio. Therefore, it is required to select the switching elements **23** each having a higher withstand voltage.

The step-up transformer **24** boosts the AC voltage generated through use of the switching element **23**. A ratio between the numbers of turns of a primary winding and a secondary winding in the step-up transformer **24** is set to from 2 times to 200 times. One end on the secondary winding side is connected to the ignition plug **50** through the resonance coil **25**, and the other end on the secondary winding side is set at the same potential as that of an engine casing. The AC voltage boosted by the step-up transformer **24** is further boosted through use of LC resonance.

An electrostatic capacitance C component in the LC resonance is a combination of the stray capacitance of the ignition plug **50** and the stray capacitance of a wiring extending from the resonance coil **25** to the ignition plug **50**. Meanwhile, an inductance L component in the LC resonance is a combination of the inductance of the resonance coil **25**, the leakage inductance of the step-up transformer **24**, and the inductance of a wiring extending from the step-up transformer **24** to the ignition plug **50**.

The step-up transformer **24** is not always required to be provided as a component, and the system can be downsized when the step-up transformer **24** is not provided as a component. However, when the step-up transformer **24** is not provided as a component, it is required to cause a barrier discharge to occur by boosting the voltage only by the DC/DC converter **22** and the LC resonance. Therefore, a load imposed on the DC/DC converter **22** increases, and there is a risk that a barrier discharge may not occur due to insufficient voltage boosting in the first place.

In contrast, when the step-up transformer **24** is provided as a component, it is possible to reduce a step-up ratio required for the DC/DC converter **22** and the LC resonance.

In the same manner, the resonance coil **25** is not always required to be provided as a component, and the system can be downsized when the resonance coil **25** is not provided as a component. In contrast, when the resonance coil **25** is provided as a component, it is possible to lower the resonance frequency of the AC voltage in the LC resonance. This allows a more inexpensive element to be used as the switching element **23**, and also facilitates insulation measures in a high voltage path.

As the resonance coil **25**, for example, an iron-core reactor using a ferrite core may be employed, or an air-core reactor using no core material may be employed. When the iron-core reactor is employed, a larger inductance can be obtained. Meanwhile, when the air-core reactor is employed, it is not required to take the heat generation of a core material into consideration.

In another case, the voltage from the DC power supply **21** may be directly converted into AC by the switching element **23** without being boosted by the DC/DC converter **22**. In the case of the direct conversion into AC, there is an advantage that the DC/DC converter **22** is not required. In contrast, the step-up ratio required for the step-up transformer **24** and the LC resonance using the resonance coil **25** and the ignition plug **50** increases, and hence the size of the system increases.

FIG. **3** is a schematic view for illustrating an example of the ignition plug **50** of the ignition device according to the first embodiment of the present invention. The ignition plug **50** in the first embodiment includes electrodes configured to cause a barrier discharge to occur. More specifically, the ignition plug **50** includes a first electrode **52**, a dielectric body **53**, a second electrode **54**, and a discharge region **55**.

The ignition plug **50** has a structure in which at least one of the first electrode **52** and the second electrode **54** is covered with the dielectric body **53**. The first electrode **52** (center electrode **52**), which is a rod-shaped conductor, is arranged on the center axis of the ignition plug **50**. The first electrode **52** has one end connected to the resonance coil **25** and the other end reaching the discharge region **55**.

The center electrode **52** excluding a portion thereof connected to the resonance coil **25** is covered with the dielectric body **53** in all directions. The entire periphery of the dielectric body **53** is covered with the second electrode **54** (peripheral electrode **54**). That is, the center electrode **52**, the dielectric body **53**, and the peripheral electrode **54** have a common center axis, and are all integrally fixed.

In the discharge region **55**, a gap (discharge gap) of 3.0 mm or less is formed between the dielectric body **53** and the peripheral electrode **54**. In this discharge gap, a barrier discharge for igniting an air-fuel mixture occurs. Through the formation of the gap, a material thickness of the dielectric body **53** is reduced in the discharge region **55** to as thin as from 0.1 mm to 5 mm.

In the discharge region **55**, it is not always required to form a gap between the dielectric body **53** and the peripheral electrode **54**. When the gap is not formed, there occurs a barrier discharge along the creepage face of the dielectric body **53** from a position at which three substances of the dielectric body **53**, the peripheral electrode **54**, and ambient gas are brought into contact with one another.

The barrier discharge on the creepage face is a discharge disadvantageous for ignition due to an influence of a flame-out action. Meanwhile, the barrier discharge on the creepage face is advantageous in that power consumption can be suppressed and that the discharge start voltage can be lowered.

As the material thickness of the dielectric body **53** decreases, the electrical or mechanical strength of the dielectric body **53** decreases, but the discharge gap can be set larger, which is advantageous for ignition. In contrast, as the material thickness of the dielectric body **53** is set larger, the electrical or mechanical strength is further improved, but the discharge gap decreases, which is disadvantageous for ignition. In addition, when the material thickness of the dielectric body **53** is set larger, thermal stress due to a temperature gradient in a radial direction increases.

The dielectric body **53** and the peripheral electrode **54** other than the discharge region **55** may be in contact with each other, or air or an air-fuel mixture made of air and fuel may exist therebetween. The dielectric body **53** and the peripheral electrode **54** may be in contact with each other only partially in the discharge region **55**, and by adjusting the area of a contact region between the dielectric body **53** and the peripheral electrode **54**, it is possible to adjust the temperature of the ignition plug **50** while the engine is running.

FIG. **4** is a schematic diagram for illustrating an example of a waveform of the AC voltage to be applied to the ignition plug **50** under a normal state in the ignition device according to the first embodiment of the present invention. As illustrated in FIG. **4**, an AC voltage over a plurality of cycles is applied to the ignition plug **50** with one ignition. As a result, the barrier discharge is carried out for a predetermined time period, and low-temperature plasma is formed, to thereby ignite the fuel.

The voltage gradually increases in the initial stage of a voltage waveform illustrated in FIG. **4**, which indicates a characteristic of the LC resonance. A time period during which an AC voltage is to be applied with one ignition, including a period for the LC resonance, is hereinafter referred to simply as "application time period".

The application time period determination portion **11** has a function of determining the application time period prior to the ignition. The longer application time period is advantageous in stable ignition, while the shorter application time period is advantageous in terms of power consumption. For example, in regard to the operating condition of the internal combustion engine, the application time period can be set longer under a condition in which the ignition tends to be unstable, and can be set shorter under a condition in which the ignition tends to be stable.

The application time period is not always required to be determined by the ignition device. In an exemplary case of an automobile, an ECU may determine the application time period and transmit information on the application time period to the AC power supply **20** depending on the length of an ignition signal. In addition to the application time period, it is also possible to adjust the power consumption with one ignition by increasing or decreasing the frequency at which the AC power supply **20** oscillates.

When the voltage is constant, the power consumption is proportional to the frequency. Meanwhile, when the voltage is boosted through use of the LC resonance, the voltage can be lowered to reduce the power consumption by increasing a distance from the resonance frequency. The ignition device according to the first embodiment selectively adjusts the application time period and the frequency, to thereby be able to perform control between, for example, a high-output short-time-period discharge at high rotation of the internal combustion engine and a low-output long-time-period discharge at low rotation thereof.

The AC voltage waveform is not limited to a sine wave, and may be, for example, a square wave. The square wave has stricter requirement specifications required for the AC power supply **20**, but can cause a larger amount of discharge to occur than that in the case of the sine wave, which is advantageous in reliable ignition. In contrast, the use of the sine wave is advantageous in downsizing and cost reduction.

FIG. **5** is a schematic diagram for illustrating an example of a waveform of the AC voltage to be applied to the ignition plug **50** under an abnormal state in the ignition device according to the first embodiment of the present invention. In this case, the "abnormal state" refers to a state in which the dielectric body **53** in the discharge region **55** of the ignition plug **50** has been damaged and there is a path having no dielectric body **53** interposed in the gap between the center electrode **52** and the peripheral electrode **54** in the combustion chamber **100**.

Typical causes of the damage done to the dielectric body **53** include an electrical penetration failure due to the applied AC voltage, an impact failure due to the collision of foreign matter, and damage due to thermal stress. Even for any one of the causes, thermal plasma is generated when the dielectric body **53** is so damaged as to expose the central electrode **52**. Thus, it becomes impossible to cause a barrier discharge to occur.

The voltage waveform illustrated in FIG. **5** indicates a phenomenon in which the voltage gradually rises due to LC resonance in the initial stage of the application of the AC voltage, and thermal plasma is caused to occur after the discharge start voltage is reached, to thereby cause the voltage to drop. The presence or absence of thermal plasma in the ignition plug **50** is determined by the thermal plasma detection portion **12**.

For example, in the AC power supply **20**, the presence or absence of thermal plasma in the ignition plug **50** can be estimated with accuracy from a change in voltage waveform or change in current waveform at any given spot. In another case of an automobile, the presence or absence of thermal plasma in the ignition plug **50** may be determined from a power consumption amount or voltage drop of a battery, and in this case, the accuracy is low, but the low cost can be achieved.

At the generation of thermal plasma, a larger current flows through the center electrode **52** than at the generation of low-temperature plasma, and the thermal plasma that has once occurred is sustained while the AC voltage is being applied. This causes output to exceed a permitted value in the AC power supply **20** when thermal plasma occurs, which raises a fear that the AC power supply **20** may cause a failure. Therefore, in order to avoid a failure of the AC power supply **20**, when thermal plasma is detected, it is required to set the application time period shorter to reduce a load on a power supply.

FIG. **6** is a schematic flow chart for illustrating an example of a control flow of the ignition device according to the first embodiment of the present invention. In Step S**101**, the control unit **10** determines, by the application time period determination portion **11**, the application time period before ignition is started. After that, in Step S**102**, the control unit **10** controls the AC power supply **20** to apply an AC voltage to the ignition plug **50** based on the application time period determined in Step S**101**.

Then, while the AC voltage is being applied, in Step S**103**, the control unit **10** determines, by the thermal plasma detection portion **12**, the presence or absence of thermal plasma. When the control unit **10** determines that thermal plasma is present, the control unit **10** advances to Step S**104** to shorten the application time period.

This processing of Step S**104** for shortening the application time period is applied from a cycle at a time point at which thermal plasma is detected, to thereby be able to reliably reduce the load on the power supply. In another case, the control unit **10** may shorten and set the application time period from a cycle following the cycle at a time point at which thermal plasma is determined to be present or after the determination is performed a plurality of times. In that case, the load on the power supply increases for a certain time period, but it is possible to improve robustness against a malfunction due to noise.

When the application time period is shortened in Step S**104**, the control unit **10** sets a time period after thermal plasma is detected until the application is to be stopped so as to ensure a time period corresponding to at least half a cycle of the AC voltage. Under a state in which thermal plasma is generated by the ignition plug **50**, no barrier discharge is generated. Therefore, under this state, the ignition is performed by the thermal plasma, but stable ignition requires a time period corresponding to at least half a period.

Therefore, in order to carry out the stable ignition in combination with protection of the AC power supply **20**, it is required to set the application time period obtained after the shortening to become shorter than the preset application time period so that the time period after thermal plasma is detected until the application is to be stopped corresponds to the time period corresponding to at least half a cycle of the AC voltage.

For example, it is assumed that thermal plasma is detected at a time point of 1.5 ms after the application of the AC voltage when an AC voltage of 5 kHz is set with an application time period of 3 ms under a normal state. In this case, a cycle of the AC voltage is 0.2 ms, and half a cycle is 0.1 ms. Therefore, the control unit **10** resets the application time period obtained after the shortening so as to become equal to or longer than 1.6 ms and shorter than 3.0 ms after the application of the AC voltage.

When a time period obtained by adding half a cycle of the AC voltage after the time point of the detection of thermal plasma becomes longer than the preset application time period, the control unit **10** preferentially sets the shorter application time period. That is, the control unit **10** prevents the application time period to be reset from becoming longer than the preset application time period.

As described above, according to the first embodiment, there is provided a configuration in which the presence or absence of thermal plasma is detected during the ignition processing, and when thermal plasma is determined to have occurred, the time period to apply the AC voltage to the ignition plug is shortened. There is also provided a configuration in which the application time period can be reset so that the time period corresponding to at least half a cycle of the AC voltage is ensured as the time period after thermal plasma is detected until the application is to be stopped.

As a result, it is possible to achieve the barrier-discharge-type ignition device capable of avoiding a failure while maintaining minimum ignition performance even when the dielectric body of the ignition plug electrically breaks down. That is, it is possible to achieve the ignition device capable of igniting fuel with stability without causing a failure in the ignition device even when the ignition plug is damaged.

Second Embodiment

A second embodiment of the present invention aims at further expansion of the function of the ignition device according to the first embodiment described above by adding a partial component thereto. In the following description, portions configured to perform the same functions as those in the first embodiment described above are denoted by the same reference symbols, and duplicate descriptions are omitted as appropriate.

FIG. **7** is a schematic diagram for illustrating an example of a configuration of an ignition device according to the second embodiment of the present invention. The second embodiment further includes a thermal plasma retention detection portion **13** configured to detect whether or not thermal plasma is retained for a period exceeding a time period corresponding to half a cycle of the AC voltage generated by the AC power supply **20** to output a thermal plasma retention signal. The thermal plasma detection portion **12** described in the first embodiment is used for the detection of thermal plasma. The thermal plasma retention detection portion **13** then determines whether or not the state in which thermal plasma is present, which is detected by the thermal plasma detection portion **12**, is retained.

The case in which the thermal plasma that has once occurred is retained without disappearing during the period of applying the AC voltage is described above with reference to FIG. **5**. However, thermal plasma may not always be retained, and may occur intermittently.

FIG. **8** is a schematic diagram for illustrating an example of a waveform of an AC voltage exhibited when thermal plasma intermittently occurs in the ignition device according to the second embodiment of the present invention. When thermal plasma occurs, the LC resonance is no longer established. Therefore, an amplification period of a voltage due to the LC resonance occurs again.

The thermal plasma is retained when a time period during which the positive or negative of the AC voltage is reversed is shorter than a time period during which the thermal plasma that has occurred disappears. In contrast, the thermal plasma disappears when the time period during which the positive or negative of the AC voltage is reversed is longer. That is, as the frequency of the AC voltage becomes lower, thermal plasma is more likely to occur intermittently. One of the features of the second embodiment is that a method of adjusting the application time period is changed depending on whether or not it has been detected that the thermal plasma is retained.

FIG. **9** is a schematic flow chart for illustrating an example of a control flow of the ignition device according to the second embodiment of the present invention. Step S**101** to Step S**103** are the same as those in the first embodiment described above. When it is determined in Step S**103** that thermal plasma is present, the control unit **10** advances to Step S**201** to determine whether or not the retention of the thermal plasma has been detected by the thermal plasma retention detection portion **13**.

When it is determined in Step S**201** that the retention of the thermal plasma has been detected, the processing advances to Step S**104**, and the control unit **10** shortens the application time period.

Meanwhile, when it is determined in Step S**201** that the retention of the thermal plasma has not been detected, that is, when it is determined that thermal plasma occurs intermittently, the processing advances to Step S**202**. In Step S**202**, the control unit **10** discriminates the operating condition of the internal combustion engine.

Specifically, the control unit **10** discriminates this operating condition based on the rotation speed of the internal combustion engine. The power supplied from the AC power supply **20** increases as the rotation speed becomes higher. Therefore, when the rotation speed is high, the control unit **10** places high priority on the protection of the AC power supply **20**, and advances to Step S**203** to shorten the application time period.

Meanwhile, when the rotation speed is low, the load on the AC power supply **20** is relatively small, and hence the control unit **10** places high priority on the stable ignition, and advances to Step S**204** to extend the application time period. The control unit **10** can determine whether to branch off to Step S**203** or Step S**204** by setting a given rotation speed as a threshold value. That is, on the whole, the control unit **10** changes the setting so that the application time period becomes shorter as the rotation speed becomes higher, while the application time period becomes longer as the rotation speed becomes lower.

When executing the processing of Step S**202**, the control unit **10** may discriminate the engine condition based on the load on the internal combustion engine or the air-fuel ratio in place of the rotation speed. It is easier to perform the stable ignition under a condition that the load is high or the air-fuel ratio is low. Therefore, when the condition that the load is high or the air-fuel ratio is low is established, the control unit **10** advances to Step S**203** to shorten the application time period. Meanwhile, when a condition that the load is low or the air-fuel ratio is high is established, the control unit **10** may advance to Step S**204** to extend the application time period.

When the engine condition is discriminated based on the rotation speed, the control based on the protection of the AC power supply **20** is executed. Meanwhile, when the engine condition is discriminated based on the load or the air/fuel ratio, the control based on the stable ignition is executed. In both cases, the effect of achieving both the protection of the power supply and the stable ignition is produced.

When the retention of the thermal plasma is not detected in Step S**201**, the control unit **10** may execute processing for increasing the frequency of the AC voltage instead of discriminating the engine condition in Step S**202**. By increasing the frequency of the AC voltage, it is possible to intentionally retain the thermal plasma. As a result, it is possible to omit Step S**202**, to thereby produce the effects of simplified control and higher speed.

As described above, according to the second embodiment, there is further provided a configuration in which the time period to apply the AC voltage to the ignition plug can be changed to an appropriate value in consideration of the retention state of the thermal plasma and the engine condition. As a result, it is possible to achieve both the protection of the power supply and the stable ignition with higher accuracy than in the first embodiment described above. In particular, even when thermal plasma occurs intermittently, it is possible to appropriately adjust input energy based on the operation state of the engine.

Third Embodiment

A third embodiment of the present invention aims at further expansion of the function of the ignition device according to the second embodiment described above by adding a partial component thereto. In the following description, portions configured to perform the same functions as those in the second embodiment described above are denoted by the same reference symbols, and duplicate descriptions are omitted as appropriate.

In the third embodiment, there is further provided air-fuel ratio reduction processing for outputting a signal for lowering a mixing ratio of air to fuel in the internal combustion engine when thermal plasma is detected. FIG. **10** is a schematic flow chart for illustrating an example of a control flow of an ignition device according to a third embodiment of the present invention.

In FIG. **10**, an air-fuel ratio reduction processing step of Step S**301** is further provided in addition to the series of procedures of processing described above with reference to the flowchart of FIG. **9**. More specifically, when thermal plasma is detected in Step S**103**, the control unit **10** advances to Step S**301** to execute the air-fuel ratio reduction processing.

That is, the control unit **10** in the third embodiment lowers the air-fuel ratio when thermal plasma is detected, to thereby establish a condition that facilitates the stable ignition. By executing such air-fuel ratio reduction processing, it is possible to set the application time period shorter than in the case in which the air-fuel ratio is not lowered, to thereby facilitate the protection of the power supply. That is, when shortening the application time period later in Step S**104**, the control unit **10** can make the amount of shortening larger than that in the second embodiment described above.

In addition, by executing the air-fuel ratio reduction processing in Step S**301**, the control unit **10** can set the application time period to be obtained after the changing in Step S**203** or Step S**204** shorter than in the second embodiment described above on the whole even after the engine condition is discriminated in Step S**202**.

The control unit **10** can also place high priority on the protection of the power supply, and ignore Step S**204** to advance the processing solely to Step S**203** instead. By advancing the processing solely to Step S**203** in the processing after Step S**202**, it is possible to simplify and speed up the control.

When detecting thermal plasma, the control unit **10** outputs a signal for resetting the ignition timing, and when the air-fuel ratio is reduced, outputs a signal for retarding the ignition timing based on the reduction amount. By optimizing the ignition condition, it is possible to produce the effect of causing stable combustion even when the ignition plug is damaged.

Such a series of air-fuel ratio reduction processes can also be executed by, for example, the thermal plasma detection portion **12** included in the control unit **10**.

As described above, according to the third embodiment, there is further provided a configuration in which the condition that facilitates the stable ignition under an abnormal state in which the dielectric body has electrically broken down is established by reducing the air-fuel ratio when thermal plasma is detected. As a result, it is possible to achieve both the protection of the power supply and the stable ignition with higher accuracy than in the second embodiment described above.

REFERENCE SIGNS LIST

10 control unit, **11** application time period determination portion, **12** thermal plasma detection portion, **13** thermal plasma retention detection portion, **20** AC power supply, **21** DC power supply, **22** DC/DC converter, **23** switching element, **24** step-up transformer, **25** resonance coil, **50** ignition plug, **52** first electrode, **53** dielectric body, **54** second electrode, **55** discharge region

The invention claimed is:

1. An ignition device, comprising:

an ignition plug, for use with an internal combustion engine, and including a first electrode, a second electrode, and a dielectric body arranged between the first electrode and the second electrode;

an AC power supply configured to generate an AC voltage to be applied between the first electrode and the second electrode; and

a controller configured to:

detect whether thermal plasma has occurred between the first electrode and the second electrode, and when the thermal plasma is detected, generate a thermal plasma occurrence signal;

determine an application time period for the AC voltage during one cycle of the internal combustion engine in advance before an application of the AC voltage, and when the thermal plasma occurrence signal is generated while the AC voltage is being applied based on the application time period, change the application time period so as to shorten the application time period; and

detect whether the thermal plasma is retained during half a cycle of the AC voltage after the thermal plasma is detected, and generate a thermal plasma retention signal when the thermal plasma is retained,

wherein, when the thermal plasma occurrence signal is generated and the thermal plasma retention signal is generated, the controller is further configured to change the application time period so as to shorten the application time period.

2. The ignition device according to claim **1**, wherein, when the thermal plasma occurrence signal is generated and the thermal plasma retention signal is not generated even after the half a cycle of the AC voltage has elapsed after the thermal plasma is detected, the controller is further configured to determine the application time period based on a rotation speed of the internal combustion engine, and change the application time period so that the application time period becomes shorter as the rotation speed becomes higher.

3. The ignition device according to claim **1**, wherein, when the thermal plasma occurrence signal is generated and the thermal plasma retention signal is not generated even after the half a cycle of the AC voltage has elapsed after the thermal plasma is detected, the controller is further configured to determine the application time period based on a load on the internal combustion engine, and change the application time period so that the application time period becomes shorter as the load becomes higher.

4. The ignition device according to claim **1**, wherein, when the thermal plasma occurrence signal is generated and the thermal plasma retention signal is not generated even after the half a cycle of the AC voltage has elapsed after the thermal plasma is detected, the controller is further configured to determine the application time period based on a mixing ratio of air to fuel in the internal combustion engine, and change the application time period so that the application time period becomes shorter as the mixing ratio of air to fuel becomes lower.

5. The ignition device according to claim **1**, wherein, when the thermal plasma is detected, the controller generates a signal for lowering a mixing ratio of air to fuel in the internal combustion engine.

6. The ignition device according to claim **2**, wherein, when the thermal plasma is detected, the controller generates a signal for lowering a mixing ratio of air to fuel in the internal combustion engine.

7. The ignition device according to claim **3**, wherein, when the thermal plasma is detected, the controller generates a signal for lowering a mixing ratio of air to fuel in the internal combustion engine.

8. The ignition device according to claim **4**, wherein, when the thermal plasma is detected, the controller generates a signal for lowering the mixing ratio of air to fuel in the internal combustion engine.

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